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A high-resolution study of tides in the Delaware Bay: Past conditions and future scenarios

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[1] Tides in the Delaware Bay (USA) have been modeled from 7000 years before present (7 ka) to the present day and for selected future sea-level rise scenarios (100 years, 300 years). Historic bathymetries were constructed through use of glacial isostatic adjustment models and a very high spatial resolution (< 100 m) was used at the shoreline. Future bathymetries were obtained by extrapolating these glacial isostatic adjustment models and applying an additional eustatic sea-level rise. It was found that tides in the lower bay have remained fairly constant through time but that tides in the upper bay have increased steadily from about 4 ka to the present day; a nearly 100% increase in total. The future runs demonstrated spatially complex behavior with tidal-range changes of up to 10%.

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1. Introduction

[2] Computational models of tides have shown variation in tidal amplitudes and phases with sea level change on both global [*Egbert et al*., 1994; *Arbic et al*., 2004; *Uehera et al*., 2006] and regional [*Scott and Greenberg*, 1983; *Gehrels et al*., 1995; *Hinton*, 1996; *Shennan et al*., 2003; *Uehera et al*., 2006; *Griffiths and Peltier*, 2008, 2009; *Hill et al*., 2011] scales. Observations of tides, on the decadal to century time scale, also reveal changes [*Flick et al*., 2003; *Jay*, 2009] in amplitude and phase. Generally quantified as a change in either mean range of tide (MN—difference between mean high water and mean low water) or Great Diurnal Range (GT—difference between mean higher high water and mean lower low water), these changes can have several implications. Past tidal-range change represents an important correction to the reconstruction of former sea levels [*Shennan and Horton*, 2002]. As a potential tertiary effect of modern climate change, tidal-range changes may also have impacts on the nearshore environment, potentially increasing inundation or affecting other dependent processes [*Green*, 2010]. In shallow estuaries like the Delaware Bay, USA, where modest sea-level variations strongly influence the shape and depth of the basin, tidal changes may be significant.

[3] Most previous studies of paleotides have been carried out using bathymetries generated through the imposition of a spatially constant depth change, selected to correspond to a particular point in time [*Hinton*, 1996; *Green*, 2010; *Pickering et al*., 2012]. Using this method for the Chesapeake and Delaware Bays respectively, *Zhong et al*. [2008] and *Leorri et al*. [2011] examined the local tidal response to a single change in sea level. However, models based upon these uniform changes ignore the spatial variability associated with glacial isostatic adjustment (GIA), which can be significant even for small-scale domains. A model that provides complete coverage of the glaciation cycle and the viscoelastic mantle response to this cycle, such as the ICE/VM series described by *Peltier* [2004, and references therein] provides an accurate method of constructing past bathymetries using the mathematically detailed methodology described in *Peltier* [1994]. Tidal models incorporating these bathymetries, with their spatially variable deviations from present day, have typically focused on larger (regional to global) domains and longer (millennial) time scales [e.g., *Thomas and Sundermann*, 1999; *Shennan and Horton*, 2002; *Hill et al*., 2011]. A common conclusion was that tides respond nonlinearly to sea-level changes, in response to numerous physical mechanisms including resonance, dissipation in marginal seas, and coupling of shelf and basin tides.

[4] Significant tidal-range changes have also been observed in tide gauge data [*Flick et al*., 2003; *Jay*, 2009]. However, it has been difficult to compare these data to most previous computational studies of changing tides. Many tide gauges are located near the coast, in estuaries, harbors, and rivers; features often not resolved in the relatively coarse grids of regional and global models. Furthermore, most studies of tidal-range change have used very coarse temporal resolution (10^3–10^4 years), making comparisons with relatively short (10^2 years) gauge records problematic.

[5] Accurate estimates of past sea-level variability provide a context for scenarios of future sea-level rise [*Engelhart and Horton*, 2012] and constraints on models that seek to understand sea-level climate relationships in the recent geological past and near future [*Kemp et al*., 2011]. However, sea-level reconstructions based upon tide-level indicators will differ from the “true” sea-level if tidal range changed through time [*Hill et al*., 2011). The Delaware Bay is an ideal test site because relative sea level data [e.g., *Engelhart et al*., 2009] in this region

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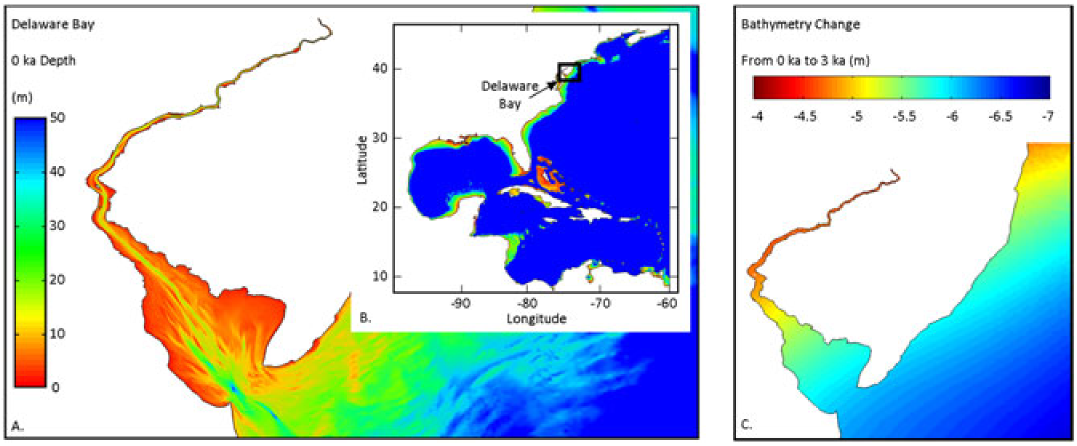

Figure 1. (A) Spatial plot of the bathymetry from the present-day (0 ka) baseline grid zoomed into the Delaware Bay. (B) Present-day bathymetry of the entire baseline grid in the northwestern Atlantic. (C) Bathymetry change from 0 ka to 3 ka in the Delaware Bay representing the spatially variable change applied to the baseline case bathymetry to create the 3 ka bathymetric grid.

demonstrate variability in the late Holocene rate of rise between the inner and outer estuary. *Leorri et al*. [2011] have suggested that this may be partly due to changes in tidal range.

2. Method

[6] A high-resolution model grid, representing the present-day bathymetry and coastline of the Delaware Bay, was created for this study. This finite element mesh contained nodes with a spacing of 80–175 m in the Delaware Bay and was based on present-day hydrographic survey and coastline data from NOAA's National Geophysical Data Center. After construction, this grid was combined with the more coarsely resolved Western North Atlantic grid of *Mukai et al*. [2002] to form a baseline 0 ka (present day) condition with a regional coverage and local focus (Figure 1a,b).

[7] Paleobathymetries were created by applying spatially variable change factors to the depths in the baseline grid for time slices between 7000 years before present, or kiloannum (ka), and 0.5 ka at 0.5 thousand year (kyr) intervals. These factors were based on the most recent ICE-6 G/VM5b data for the eastern U.S. coast as explained in *Engelhart et al*. [2011]. Figure 1c shows the spatial variability of these factors where the modeled bathymetry change from present day is greater in the Atlantic Ocean than in the northern Delaware Bay, a result first noted by *Leorri et al*. [2006]. Morphologic changes from temporally shorter-term forcing such as nontidal wave driven energy and river inflow were not incorporated. Relative to GIA, these processes are not yet well documented on the longer time scales being studied here.

[8] For future scenarios, the baseline grid was first modified to include present-day topographic data, allowing sea-level rise to inundate presently dry areas. The ICE-6 G/VM5b data from 0.5 ka to present day were next extrapolated forward to time slices of +0.1 kyr and +0.3 kyr and applied to this new baseline grid, representing an estimated influence of GIA. Finally, eustatic factors of 1.01 and 3.5 m of sea level rise, for +0.1 and +0.3 kyr, respectively, were applied to the depths. These factors are median estimates taken from *Rahmstorf et al*. [2011] and *Schaeffer et al*. [2012], and correspond to the RCP4.5 scenario. This scenario corresponds to only minor adjustments of the energy and industry sectors [*Wise et al*., 2009] and peak warming of 3°C by 2300.

[9] Offshore open boundary tidal forcing was imposed on a single boundary along the 60th meridian and was obtained from TPXO 7.2 [*Egbert et al*., 1994]. The open boundary forcing was held constant in time, justified on the following grounds. First, the ICE-6 G/VM5b model showed the Delaware Bay to be dry prior to 7 ka. Second, *Hill et al*. [2011] demonstrated, based upon *Griffiths and Peltier* [2008, 2009] that northern Atlantic Ocean tides experienced little basin-scale change between that period and present day. Tide-driven water surface elevations and tidal constituent amplitudes and phases were obtained by applying the two-dimensional depth integrated Advanced Circulation (ADCIRC) model [*Luettich and Westerink*, 1991] for 90 model-day runs over each bathymetric grid. Wetting and drying algorithms were enabled for all simulations, allowing for determination of the extent of the intertidal zone. Output constituent amplitudes and phases were used to calculate tidal datums, such as mean higher high water, using the method of *Mofjeld et al*. [2004]. Tidal-range change was then quantified by calculating the temporal and spatial variability of GT.

[10] The 0 ka grids, both with and without topographic data, were validated by comparing the model output both to water surface elevation time series data and tidal constituent amplitude and phase data, as obtained from NOAA tide gauges (Table 1). Model errors increased slightly with distance up-bay.

3. Results

[11] Regionally, bathymetric changes did not cause the basin shape of the Atlantic Ocean to change significantly over the interval modeled. On a local level, however, the Delaware Bay was found to have been completely dry prior to 7 ka. The bay slowly inundated from 7 ka to present day with tidal influence reaching the upper bay at 3–4 ka. Shoreward inundation can be seen between 3 ka, 0 ka, and +0.3 kyr, forming different coastlines with respect to the 0 ka condition (black line) in each of the panels of Figure 2.

Table 1. Percent and Degree Differences Between Modeled and NOAA Calculated M_2 Constituent Amplitudes and Phases for Seven Locations in Delaware Bay. Modeled Values Were Calculated Using the Baseline Grid With a Boundary at the Present-Day Coastline. Values Calculated Using the Combined Bathy/Topo Grid Showed Slightly Larger Errors, but Most Stations Were Within 10% Amplitude and 15° Phase of NOAA Constituents

Location (From Lower to Upper Bay)	M_2 Amplitude (% Difference)	M_2 Phase (° Difference)
Lewes, DE	0.3	5.3
Cape May, NJ	1.7	3.2
Brandywine Shoal, NJ	2.2	3.2
Ship John Shoal, NJ	7.6	3.3
Delaware City, DE	9.3	4.1
Philadelphia, PA	8.3	7.5
Newbold, PA	4.2	14.3

3.1. Historic Simulations

[12] While regional tidal model results showed minimal changes to deep-ocean GT over time (7 ka to present day), results in the Delaware Bay showed significant spatial and temporal variability. The variability within the Delaware Bay can be seen in Figure 2, which shows contours of GT at 2.5 ka, 0 ka, and +0.3 kyr. Present-day GT is largest in the Delaware River and northeast upper portion of the bay at around 1.8 m. Ranges at the mouth in the lower bay are closer to 1.4 m further decreasing with distance from the bay mouth moving out onto the shelf. At 2.5 ka, low GT values of less than 1 m are seen in the upper bay while the lower bay tides are of similar magnitude to those at present day, indicating a sharp spatial gradient in the temporal rate of change in GT.

[13] Figure 3 illustrates this spatial gradient with greater temporal resolution. GT values at two locations representative of the upper and lower bay (marked with crosses in Figure 2) are shown as a function of time, from 5 ka to +0.3 kyr. In the lower bay, tides steadily fell from 5 ka to 1.5 ka (by approximately 30%), remaining essentially constant from 1.5 ka to present day. In the upper bay, however, GT has steadily risen from 4 ka to present day; a total increase of about 140%. The bathymetric changes at these two locations, with respect to present day, and GT values (where available) are summarized in Table 2.

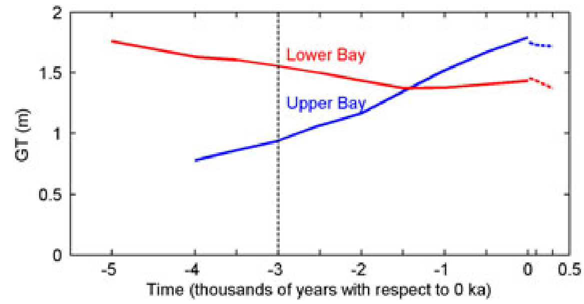

Figure 3. Time series of GT (meters) at the two characteristic locations showing different time-wise behavior both upon inundation and over the course of the same period. Solid and dashed lines represent past and future cases, respectively. The temporal resolution of this plot is between 0.1 and 0.5 kyr.

3.2. Future Simulations

[14] Figures 2c and 3 provide results for the future simulations. In addition to runs at +0.1 kyr and +0.3 kyr, a run with the combined topo/bathy grid was done at 0 ka. The slight discontinuity observed at 0 ka in Figure 3 is due to the differences in the two grids used. The original grid had a boundary (black line in Figure 2) at the present-day coastline. Although wetting and drying were enabled for all simulations, wetting inland of this boundary was not allowed. As shown in Figure 2c, the eustatic rise assumed at +0.3 kyr, when applied to the combined topo/bathy grid, led to substantial inundation inland of this boundary. Overall, the results for future GT are a departure from the historical runs, with decreases (about 10% at +0.3 kyr) observed. The rates of decrease in the upper and lower bay regions are found to be fairly similar, also a departure from the historical runs, where sharply differing rates were observed.

4. Discussion

[15] The paleobathymetries reveal that the Delaware Bay evolved steadily from a narrow river (~ 4 ka) to the familiar funnel-shaped bay of the present day. It is well known [e.g., *Parker*, 1991] that funnel-shaped estuaries exhibit amplification of tides with up-bay distance, primarily

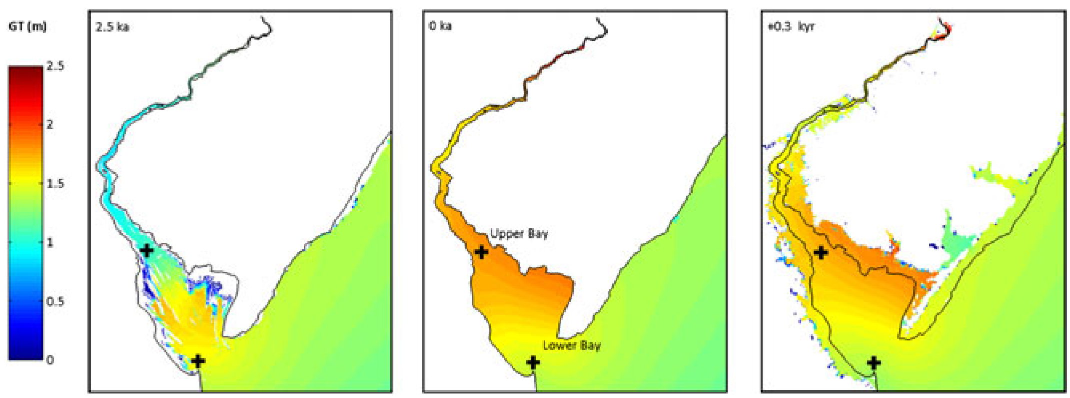

Figure 2. Panels showing spatial plots of GT (meters) through the Delaware Bay at 2.5 ka, 0 ka, and +0.3 kyr. Spatial variability is shown by the differences in color within each panel while temporal variability is shown by the differences between panels. Two locations are shown where the characteristic upper bay and lower bay tides were further analyzed.

Table 2. Bathymetric Adjustments (From Present Day) and Great Diurnal Range (GT) Calculations at Upper and Lower Bay Locations (Figure 2) at Model Time Slices (When Available)

Time (ka)	Location			
	Lower Bay		Upper Bay	
	Latitude N(°)			
	38.8358		39.2764	
	Longitude W(°)			
	75.093		75.357	
	Δ*h* (m)	GT (m)	Δ*h* (m)	GT (m)
0	0	1.43	0	1.79
1	–1.69	1.38	–1.44	1.52
2	–3.94	1.43	–3.42	1.16
3	–6.04	1.55	–5.35	0.93
4	–8.62	1.63	–7.79	0.78
5	–13.00	1.76	–12.00	
6	–18.98		–17.70	
7	–26.23		–24.91	

due to nonlinear overtides. This spatial structure of tidal amplitudes, and the Delaware Bay's evolution toward the geometry needed to produce it, is the most likely explanation for the large changes in upper bay GT, compared to the lower bay. The decreases in GT that were observed in the future runs are most likely due to the extensive shallow regions that were added under the various sea-level rise scenarios. Conceptually, this is similar to numerous previous studies [e.g., *Green*, 2010] that have demonstrated the role of shallow marginal seas (shelf regions) in dissipating tidal energy and limiting regional tidal amplitudes.

[16] This high temporal and spatial resolution of the present study enabled comparisons to the tidal gauge record analysis of *Flick et al*. [2003]. Their analysis was limited to two locations (Lewes, DE and Cape May, NJ) within the lower Delaware Bay, both of which showed noticeable decreases in GT (–33 and –51 mm/100 yr, respectively). The +0.1 kyr simulation of the present study produced estimates of –32 and –22 mm/100 yr. The +0.3 kyr simulation yielded estimates of –40 and –24 mm/100 yr. The general agreement suggests that tidal modeling is a useful tool in predicting future changes in tidal parameters.

[17] The lack of sedimentation and geomorphologic evolution in the present study is consistent with previous studies of paleotides. *Kim et al*. [2004] have estimated sedimentation rates at two sites in southern Delaware Bay to be approximately 3 mm/yr, which is consistent with local sea-level rise rates [*Stumpf*, 1983]. *Morris et al*. [2002] have suggested that salt marshes should be able to adapt to a maximum value of 12 mm/yr of sea-level rise. However, *Kirwan et al*. [2010] have refined this, suggesting that the threshold rate of sea-level rise is a function of tidal range and suspended sediment concentration. For values typical of the Delaware (tidal range ~1.5 m, suspended sediment concentration ~10–15 mg/l [*Sommerfeld and Wong*, 2011]), this threshold rate appears to be ~5 mm/yr.

[18] The present results show good agreement with the trends of a similar model study by *Leorri et al*. [2011]. Their local model was forced with only one constituent (M2) that was assumed to be spatially constant on their open boundary. Additionally, their model considered only one paleotidal simulation that was created with a spatially uniform decrease in water level. They describe their decrease of 5 m as representative of 4 ka, but according to the ICE-6 G/VM5b model used here, that decrease is more representative of 3 ka (on average; there is a ~1 m variation in GIA from the outer to inner bay at that model time slice). In their study, a similar trend in the M2 constituent was noted, showing the characteristic spatial variability between the upper and lower bay. The present study's use of spatially variable depth changes shows that this tidal variability was slightly different in magnitude and the greater temporal resolution of the present study helps to constrain the temporal history of these tidal changes.

[19] Applying the modeling to the data of *Engelhart et al*. [2009] allows us to estimate the effect of GT change on the rate of late Holocene relative sea-level rise. The small change in GT in the lower bay results in no difference between the tidal-range change corrected values and those reported by *Engelhart et al*. [2009]. Despite the large magnitude of the percentage increase in GT for the upper bay during the late Holocene (> 100%), the rate of late Holocene relative sea-level rise in the upper bay decreases by only 0.1 mm/yr from 1.7 ± 0.2 to 1.6 ± 0.2 mm/yr because of the microtidal regime. This is in good agreement with the rate of 1.55 mm/yr suggested by *Leorri et al*. [2011]. These small GT changes suggest that late Holocene rates of rise are reliable estimates of the glacial isostatic adjustment of the predominantly microtidal (< 2 m) U.S. Atlantic coast as they are unlikely to be subject to errors greater than 0.1 mm/yr. However, similar percentage changes in GT in a macrotidal regime (e.g., Bay of Fundy) would produce more significant differences. This highlights the importance of choosing sites that have a microtidal (< 2 m) regime when constructing high-resolution records of relative sea-level rise [e.g., *Kemp et al*., 2011].

5. Conclusions

[20] Models of past and future tides in the Delaware Bay, carried out with high temporal and spatial resolution, showed significant changes in tidal range throughout time. Historic tidal ranges were shown to increase at a much faster rate in the upper bay than the lower bay, mostly agreeing with a previous study *Leorri et al*. [2011]. The more complex and complete models presented here broadly agree with their results, indicating a 0.1 mm/yr difference in rates of late Holocene relative sea-level rise in the upper bay when tidal-range changes are accounted for. Future simulations suggested decreases in tidal range generally consistent with recent analyses of tide gauge observations.

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